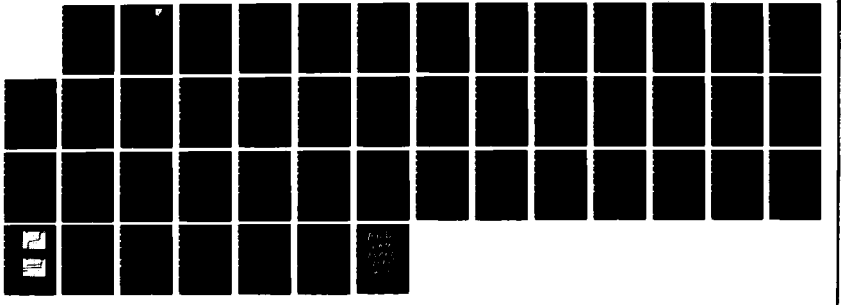
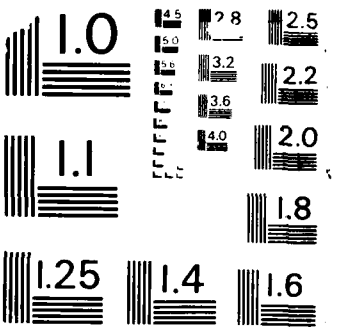
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THE SUPERCONDUCTING PHASE SHIFTER IN THE DEVELOPMENT OF A TERAHERTZ IMAGING RADAR SYSTEM

HYPRES, Inc.

S. Baliga, M. Radparvar and S. M. Faris

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Air Force Systems Command
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A Terahertz Imaging Radar System which exploits superconductive electronics for all of its major components is described in this report. In particular, the importance of the superconducting millimeter (mm) wave phase shifter in the development of such systems has been fully investigated. The experimental and theoretical results presented here are better than we expected to achieve under Phase I of the project. Conventional technology is unable to provide the high frequencies required to obtain small apertures for target acquisition. Superconducting technology offers a high performance, very broadband and low power, mm and sub-mm wave phase shifter based on superconducting microstrips. The physics of the non-equilibrium superconductivity underlying the operation of the superconducting microstrip phase shifter has been studied. Theoretical analysis and numerous experimental results show that superconducting stripline modulation leading to phase velocity reduction and subsequent phase shift is achievable by quasi-particle injection. A digital N-bit phase shifter based on the superconducting microstrip transmission line is proposed for development.

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The implementations of such a mm and sub-mm wave phase shifter will fulfill a crucial need in the development of the Terahertz Imaging Radar.

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ABSTRACT

A theoretical study has been made of the physics of the non-equilibrium superconductivity underlying the operation of the superconducting microstrip phase shifter. The penetration depth of some superconductors has been studied and a relation between penetration depth and quasi-particle density obtained. The power loss in transmission, in superconductors, has been analyzed as a function of frequency, to ascertain the limits of performance of the phase shifter. The results show that the superconducting phase shifter can operate at frequencies as high as the gap (0.7 THz in Nb). Injection mechanisms, to locally weaken superconductivity and perform strip line modulation have been studied. A digital superconducting phase shifter is proposed for use in Terahertz Imaging Radars. The above studies show that the superconducting phase shifter offers high performance, with very broad bandwidth and low power dissipation and will fulfill a critical need in the design and operation of mm and sub-mm wave imaging radars.

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INTRODUCTION

The design and operation of phased array antennas, operating in the mm wave and sub-mm wave regions of the electromagnetic spectrum is strongly dependent on the availability of passive and active components such as transmission lines, local oscillators, phase shifters, etc.. Critical to the design of these systems is the develcpment of the phase shifter, since the beam from an array can be scanned, or switched from one position to another, in time limited by the switching speed of this device[1]. Current phase shifters based on conventional technologies, cannot handle these frequency requirements. Besides their limited bandwidth, conventional devices are constrained by their power requirements.

Superconducting technology offers a high performance, very broadband and low power, mm and sub-mm phase shifter based on superconducting microstrip interferometers. This unique phase shifter combines the physics of non-equilbrium superconductivity with high performance superconducting transmission lines to achieve continuous modulation of the phase velocity by electronic or optical means. Phase shifters designed from these interferometers are expected to provide extremely wide bandwidths (hundreds of gigahertz), and very high speed (sub-nanosecond) responses for wavelengths less than one millimeter. The thin film fabrication of microstrips will ensure large scale reproductability and permit numerous circuits on a wafer, as required for a large number of phase shifters. In addition to high resolution imaging radar applications, the large bandwidths, small antenna sizes and narrow beamwidths permitted at these frequencies, lend themselves to applications in low-angle tracking, interference free radar, cloud physics radar, electronic counter-counter-measures (ECCM), fuzes and missile guidance[1].

In this paper, we investigate the physics of non-equilibrium superconductivity as it applies to the design of superconducting phase shifters. We study propagation and losses in superconducting transmission lines for the very high frequencies (hundreds of gigahertz), needed for sub-mm wave operation of phase shifters. Results obtained by various experimenters, are reported to show the feasibility of the superconducting phase shifter.

Penetration Depth and Quasi-Particle Density

The London equations describing the behavior of superconductors in a magnetic field predict that currents and magnetic fields in superconductors can exist only within a layer of thickness λ_L of the surface. λ_L is given by[2]

$$\lambda_L^2 = m^*/e^{*2} n_0 \mu_0 \qquad ---(1)$$

where m^* is the effective pair mass
e^* is the effective charge of a pair
n_p is the density of Cooper pairs.

The superconducting state can be described[2], as asserted by Ginzburg and Landau by a complex order parameter $\Psi(\bar{r})$, which vanishes at temperatures above Tc and whose magnitude measures the degree of superconducting order at position $\bar{r}$. The magnitude of $\Psi(\bar{r})$ may be identified in the Ginzburg-Landau theory with the density of Cooper pairs,

$$|\Psi|^2 = n_p \qquad ---(2)$$

Combining Eq. 1 and Eq. 2 we get

$$\lambda_L^2 \propto 1/|\Psi|^2 \qquad ---(3)$$

Gorkov has shown[2] that Ψ is directly proportional to the energy gap parameter Δ. This implies a relation between λ and Δ[3],

$$\frac{\lambda_L(n,T)}{\lambda_L(0,T)} = \frac{\Delta(0)}{\Delta(n)} \qquad ---(4)$$

where n is the normalized excess quasi-particle density in units of 4 $N(o)\Delta(o)$, N(o) being the Bloch density of states. T is the temperature in Kelvin of the superconducting sample. The value of n depends on temperature, magnetic field and quasi-particle injection.

The above phenomenological expression reveals that significant modification of the penetration depth can be realized through suppression of the energy gap by any of the means mentioned above.

The dependence of energy gap on excess quasi-particle density n, is given for small n, by[4]

$$\frac{\Delta(n)}{\Delta(o)} \approx 1 - 2n \qquad ---(5)$$

Combining Eq. 4 and Eq. 5 gives a relation between the penetration depth and the excess quasi-particle density.

$$\frac{\lambda_L(o,T)}{\lambda_L(n,T)} \approx 1 - 2n \qquad ---(6)$$

An increase in n thus leads to an increase in the penetration depth.

$\lambda L(o,T)$, in the above equations is the penetration depth at temperature T in absence of external perturbation. It is related to the penetration depth at absolute zero $\lambda_L(o)$ by the semi-empirical relation[2]

$$\lambda_L(T) = \lambda_L(0)[1 - (T/T_c)^4]^{-1/2} \qquad ---(7)$$

Knowing the value of Tc and λL at any other temperature, $\lambda L(o)$ can be obtained.

For non-granular type II superconductors such as niobium, and lead containing impurities such as Au, In or Bi, the penetration depth has been shown to be dependent on the residual resistivity $\rho(Tc)$. We have[5]

$$\lambda[\rho(T_c),T] = \lambda_L(T).[1 + \frac{\rho(T_c)\xi_o}{J(o,T).(\rho(T_c).l(T_c))}]^{1/2} \qquad ---(8)$$

where ξ_o is the coherence length
$\rho(Tc)$ is the residual resistivity
$l(Tc)$ is the electron mean free path
$J(o,T)$ is a BCS range function with values between 1 and 1.33 for T between o and Tc
$\rho(Tc).l(Tc)$ is a constant for the material

and $\lambda_L(T)$ is the penetration depth from Eq. 7.

The penetration depth is thus increased from value $\lambda_L(T)$ by its dependence on the electron mean free path and residual resistivity.

Figure 1 shows the variation of λ_L vs. the residual resistivity $\rho(Tc)$ for Nb films.

Since the room temperature resistivity and residual resistivity for niobium are related by Mathiessen's rule[6] as

$$\rho(300\ K) - \rho(10\ K) \approx 14.5\ \mu\Omega\text{-cm} \qquad ---(9)$$

λ_L can also be obtained as a function of the room temperature resistivity. The room temperature resistivity can be conveniently obtained from the square resistance measurement $R_\square(300K)$ and the film thickness d, as

$$\rho(300\ K) = R_\square(300\ K)d \qquad ---(10)$$

Figure 2 shows the relation between penetration depth and the residual resistivity $\rho(Tc)$ for lead containing impurities. The fit to Eq. 8 is evident.

Eq. 8 which is valid for non-granular type II superconductors, is not valid in the case of NbN. Here the Ginzburg- Landau theory for the BCS weak coupling case in the dirty limit with strong coupling correction yields[7]

$$\lambda L(o) = 95.3\ (\rho Tc(\mu\Omega cm)/Tc(K))^{1/2} \qquad ---(11)$$

The Eqs. 7, 8 and 11 relate penetration depth with temperature and residual resistivity, which are the parameters to be varied in implementation of the superconducting phase shifter.

Experimental evidence for the relation between penetration depth and excess quasi-particle density has been provided by Weinberg in his Master's Thesis[8]. Transmission line modulation was achieved by the use of optical radiation to suppress the energy gap, and also by temperature variation.

Loss in Superconductors and Frequency

Superconductivity may be described by a two-fluid model where the Cooper pairs give rise to only a reactive impedance, while normal electrons have both reactance and resistance. The losses associated with this resistance are very small and become important only at high frequencies.

The classical skin effect parameter δ is given by[9]

$$\delta = (2/\omega\sigma\mu)^{1/2} \qquad ---(12)$$

where ω is the frequency
and σ is the complex conductivity.

The derivation for impedance and phase velocity presented assume that the skin effect parameter δ is much larger than the London penetration depth λ_L. At lower and moderate frequencies, the skin effect parameter is about two orders of magnitude greater than the superconducting penetration depth. However, as can be seen from Eq. 12, very high frequencies can significantly reduce the skin depth, resulting in power absorption. Since the penetration depth is a function of temperature (ref. Eq. 7), lower temperatures aid in the use of higher frequencies.

The condition that λ_L be small relative to the skin depth implies an upper cutoff frequency fc, such that

$$f << 1/(\pi\lambda_L^2\mu\sigma) = fc \qquad ---(13)$$

where fc may be interpreted as the upper cutoff frequency of the wave propagating in the stripline and σ_N is the conductivity of the normal electrons, which may be approximated by

$$\sigma = (T/T_c)^4 \sigma_N \qquad ---(14)$$

where σ_N is the normal conductivity just above the critical temperature, Tc.

Both λ_L and σ are dependent upon the electronic mean free path, l. In the "clean" limit case, where $l >> \xi_o$ (ξ is the zero temperature coherence length), λ_L is nearly independent of l whereas $\sigma \sim l$. Hence, in this case $fc \sim l^{-1}$. For thin samples, where the mean free path becomes thickness limited, i.e., l > film thickness, the clean limit fc will saturate. Also, if $l > \delta$ the anomalous skin effect dominates.

In the "dirty" limit, ($l << \xi_o$), $\lambda^2 \sim l^{-1}$ and $\sigma \sim l$ (equivalently $\delta^2 \sim l^{-1}$), fc becomes independent of l.

For niobium assuming λ_L = 850 Å, $\mu = \mu_o$ and $\sigma^{-1} = \sigma_N^{-1}$ as a lower bound with $\sigma_N^{-1} = 50 * 10^{-9}$ Ω- m, the criterion for a lossless line, Eq. 13 is

$$f << 2 * 10^{12} \text{ Hz} = fc \qquad ---(15a)$$

For NbN assuming λ_L = 3000 Å and $\sigma_N^{-1} = 1500 * 10^{-9}$ Ω m, the criterion for a lossless line is

$$f << 4 * 10^{12} \text{ Hz} = fc \qquad ---(15b)$$

The higher cut-off frequency for higher Tc superconductors (e.g. NbN versus Nb) is of great significance to the

development of the superconducting phase shifter. Using the newly developed material Ba-La-Ca-O[10], critical temperatures as high as 40K can be obtained. This would imply extremely high (tens of terahertz) cut-off frequency. The simplification to the cryogenics, in reducing the close-cycle refrigerator to a single stage may also be noted.

Recent experiments by C.C. Chi et.al.[11] with coplanar superconducting niobium transmission lines have achieved dispersion-free pulse propagation upto 0.7 THz (which corresponds to the energy gap in their sample). Little attenuation is observed below the superconducting gap frequency but strong attenuation above it.

These experimental results agree well with the theoretical predictions of the Mattis-Bardeen formulation of complex conductivity in superconductors[12]. Higher transmission frequencies can be achieved if a larger gap superconducting material such as NbN is used.

BCS theory gives a better estimate of surface impedance than the two-fluid model used in Eq. 14. The surface resistance in microwave cavities is described[2] by (for $\hbar\omega < \Delta(T)$ and $T < 0.5\ T_c$)

$$R_s = \frac{(C\omega^{3/2})}{T} \exp\left[-\Delta(T)/k_B T\right] + R_o \qquad ---(16)$$

where C is a constant and R_o a temperature independent residual surface resistance.

Below the energy gap frequency (0.72 THz for niobium at 4.2K), the surface resistance of a superconductor is orders of magnitude smaller than that of a normal metal, such as copper. Also, the surface reactance below the energy gap varies as ω, making it appear exactly as an inductor. This

property yields a stripline with a very low dispersion. Above the energy gap, a superconductor behaves like a normal metal of conductivity σ_N.

The attenuation αdB is related to the real part of the propagation constant[13] ($\gamma=\sqrt{ZY}$ where Z is the series impedance and Y the shunt admittance of a unit length of line) by

$$\alpha dB = 20 Log_{10} Re(\gamma) \qquad ---(17)$$

Fig. 3 compares the attenuation in dB/m of striplines of copper and niobium at 4.2K. The superiority of the niobium stripline at frequencies below $2\Delta/\hbar$ is evident.

HYPRES has the facility and technology to fabricate films of NbN for the measurement of surface resistance. Fig. 4 shows recent results of measurements of the surface impedance of NbN fabricated at HYPRES[14]. Figs. 5 and 6 show results for the 7 to 10 GHz frequency range[15]. HYPRES is continuing in its efforts to fabricate NbN films of low surface resistance. Fig. 7 shows the variation of the surface resistance of niobium and lead as a function of temperature. Fig. 8 shows studies by NRL and MIT Lincoln Labs comparing the RF loss of niobium and niobium nitride as a function of temperature.

Injection Mechanisms

As shown in the earlier sections, suppression of the energy gap and increase in the penetration depth can be achieved by increasing the number of quasi-particles in the superconductor.

Three mechanisms possible for quasi-particle injection are:

a) heat
b) optical irradiation
c) by electrical injection

Weinberg[8] has demonstrated modulation of phase velocity in superconducting strip lines by simple temperature variation of the cryogenic environment. By raising the temperature to near Tc, reduction of the phase velocity of the strip line of approximately 75% has been observed. The experimental results verify Eqs. 4 through 7.

The relation between phase velocity Vp and λ for a microstrip line is given by[8]

$$Vp/c = \sqrt{\frac{1}{\epsilon}} \left\{ 1 + \frac{\lambda_i}{to} \coth \frac{di}{\lambda_i} + \frac{\lambda_g}{to} \coth \frac{dg}{\lambda_g} \right\}^{-1/2} \qquad (18)$$

where di is the transmission line thickness
dg is the ground plane thickness
and to is the thickness of the insulator.

From this equation, suppression of the energy gap of either the strip line or the ground plane superconductors, will increase the corresponding penetration depths, and therefore decrease the phase velocity.

The inductance of the stripline per unit length can be deduced from equation 18.

$$L = \frac{\mu t_o}{W}\left\{1 + \frac{\lambda_i}{to}\coth\frac{di}{\lambda_i} + \frac{\lambda_g}{to}\coth\frac{da}{\lambda_g}\right\} \quad (18a)$$

Where W is the width of the stripline. The capacitance of the transmission line per unit length is simply given by:

$$C = \epsilon\frac{W}{t_o} \quad (18b)$$

Where ϵ is the dielectric constant of the medium. From transmission line theory, the time delay per unit length is given by

$$\tau = \sqrt{LC} \quad (18c)$$

or

$$\tau = \sqrt{\mu\epsilon}\left\{1 + \frac{\lambda_i}{to}\coth\frac{di}{\lambda_i} + \frac{\lambda_g}{to}\coth\frac{da}{\lambda_g}\right\}^{+1/2} \quad (18d)$$

Consequently:

$$\delta T = \sqrt{\mu\epsilon}\ \frac{\left\{ -\frac{di}{\lambda_i} + \coth\frac{di}{\lambda_i} + \frac{di}{\lambda_i}\coth^2\frac{di}{\lambda_i} \right\}\frac{\Delta\lambda_i}{to}}{2\left\{ 1 + \frac{\lambda_i}{to}\coth\frac{di}{\lambda_i} + \frac{\lambda_g}{to}\coth\frac{da}{\lambda_g} \right\}^{+1/2}} \qquad (18e)$$

Where δT is the additional time delay casued by the change in the penetration depth of the stripline due to quasiparticle injection.

In order to get a numerical value for δT we assume that

$$\begin{aligned} dg &= 3000\ \text{Å} \\ di &= 3000\ \text{Å} \\ \lambda_i &= \lambda_g = 3000\ \text{Å} \\ t_o &= 3000\ \text{Å} \\ \epsilon &= 4.0 \end{aligned} \qquad (18f)$$

and $\Delta\lambda_i = 0.05\,\lambda_i$

The last equation, as we see later, restricts the change in the line impedance to a much less than 5%, which is desireable if we need to maintain the transmission line impedance close to its equilibrium value. Equations 18e and 18f will then result in

$$\delta T = 0.026\sqrt{\mu\epsilon} \qquad (18g)$$

or the phase shift for a 100 GHz signal is

$$\delta\Phi = \omega\,\delta T = 111.9 \text{ rad/m} = 6.4 \text{ degrees/mm}$$

As the film thickness (d_i) decreases, the kinetic inductance of the transmission line becomes a stronger function of the quasiparticle density. Consequently, one can arbitrarily increase the phase shift for a fixed length of superconductor by adjusting the stripline thickness. For instance, in the case of the previous example, reducing d_i to 1000 Å results in 15 degrees/mm phase shift for the same change in the penetration depth.

From $Z = \sqrt{L/C}$ and Equation 18c we get

$$\frac{\delta Z}{Z} = \frac{\delta L}{2L}$$

and

$$\frac{\delta m}{m} = \frac{\delta m}{2L}$$

or

$$\frac{\delta Z}{Z} = \frac{\delta m}{m}$$

Using numerical values given by Equation 18f, the change in the impedance is

$$\frac{\delta Z}{Z} \sim 0.02$$

which is quite acceptable and requires an IR source with 30 nW/um^2 intensity to accomplish such phase shifts.

A more novel technique for phonon injection would be to inject nonequilibrium phonons from nonradiative states in optically illuminated semiconductors such as Si or GaAs. This method has been used by Iguchi for phonon detection[16]. Light is transmitted through an optical fiber onto a Si or GaAs wafer. A film of aluminum and silicon nitride separates the silicon from the junction (in our case the strip line). The aluminum prevents direct transmission of light onto the phonon sensor and the silicon nitride isolates the aluminum.

A variation of this technique could be used to inject phonons into the strip line or the ground plane. Phonons whose energy is greater than the energy gap contribute to the pair-breaking process in the superconductor. The gap reduction is proportional to the number of phonons incident on the film per unit time.

The above technique used by Iguchi for phonon detection by a tunnel junction, can be modified to obtain a change in penetration depth and strip line modulation. The response time is, in principle, determined by the nonequilibrium lifetime of a superconductor and can be of order of nanoseconds or less.

Gap suppression by irradiation with light has been demonstrated by several experimentors, most recently by investigators at HYPRES[17,18]. Irradiation with infrared radiation produces quasi-particles in the superconducting film by the breaking of Cooper pairs, in accordance with Eq. 5. HYPRES has investigated the response of superconducting thin films, Josephson junctions and arrays of Josephson junctions to radiation in the 1 to 20 micron region, as part of an ONR project to build an infrared image processing system. Extremely high sensitivities, of the order 10^5 V/W have been obtained with the junctions

and arrays in the entire wavelength range. Such high responsivities are not possible in an entire wavelength range using conventional techniques.

Fig. 9 shows the I-V curves of a Josephson junction and of an array of 50 such junctions, with and without exposure to infrared radiation[18]. The suppression in gap on irradiation is clearly evident. HYPRES is currently working actively on Phase II of the image processor project to further enhance the device sensitivity and build an integrated image processor using superconducting technology.

Weinberg[8] has shown that the phase velocity in superconducting strip lines can be modulated by irradiation with an argon ion laser. The penetration depth increased by a factor of 1.78, corresponding to a 44% change in gap energy. The maximum reduction in phase velocity was 28% (see Eq. 18); the self-inductance increased by a dramatic 92% over its value in the equilibrium state and the impedance was observed to undergo a maximum change of 40%.

In these experiments, the sample was directly illuminated with laser light. Light could also be guided onto the sample using a fiber. The evanescent portion of an optical guided wave has also been used in an integrated optic experiment to locally weaken superconductivity in thin films of lead[19]. This last technique has the advantage of permitting a precise determination of parameters such as the geometry of the illuminated region.

The response time to optical illumination has been studied by several groups. In general, the recombination time is not that of quasi-particles alone. Phonons created by high energy quasi-particles, can decay to produce more quasi-particles, leading to a cascade. The response time can

then be limited by the phonon escape time, rather than quasi-particle recombination time. Studies by Chi et.al.[20] with picosecond laser pulses, have shown the phonon escape time to be of order of nanoseconds in lead.

Gap suppression in a superconducting thin film by electronic injection, has been studied mainly with a viewpoint of utilizing the properties in devices such as the Quiteron[21]. In this device, a tunnel junction is used as a means of injecting quasi-particles and suppressing the gap. For the purposes of weakening superconductivity, it is not necessary to have the current flow through the device of interest itself. Current flow in a control line, in proximity to the device, can be used to control the critical current.

While all three injection mechanisms; heat, light and electronic, are capable of producing gap suppression and stripline modulation, a conclusion as to which mechanism is most efficient and suitable would depend on the actual phase shifter design under consideration.

A first step towards the design and fabrication of a phase shifter would be to study the effects of optical irradiation on SQUID circuits. The change in resonance frequency on irradiation could be studied as a function of intensity, wavelength and the circuit parameters such as inductance. HYPRES has already acquired the necessary equipment[17,18] required to demonstrate the effects of optical irradiation on such circuits.

A further step leading to the actual implementation of a mm and sub-mm wave phase shifter would be to design and fabricate actual phase shifting elements. Two types of phase shifters are proposed. The first is a superconducting

microstrip interferometer (see Fig. 10) where a transmission line is split into two parts and then recombined. Quasi-particle injection into any one of the two limbs would cause a change in the phase velocity in that limb (as given by Eq. 18) and a subsequent phase shift in the recombining signals.

A second phase shifter design could be a superconducting microstrip resonant ring (see Fig. 11). Here the resonance frequency of the ring is changed by quasi-particle injection, owing to the change in phase velocity. This design has the advantage that attenuation can also be measured as a function of quasi-particle injection. HYPRES has the capability to design and fabricate both of these phase shifters.

After the properties of phase shifting under quasi-particle injection are studied using such phase shifters as microstrip interferometers and resonant rings, a practical realization of mm and sub-mm wave phase shifters can be achieved with the knowledge gained from these studies. Such a phase shifter promises high performance, with broad bandwidth and low power dissipation, and will fulfill a crucial need in the area of phased array antennas and imaging radars. To this end, HYPRES proposes the design of a digital superconducting phase shifter described in the next section.

Digital Superconducting Phase Shifter

HYPRES proposes the development of an N-bit superconducting phase shifter. Such a phase shifter has 2^N steps, with a phase shift per step of

$$\Delta\phi = \frac{2\pi}{2^N} \qquad (19)$$

Fig. 12 shows a 3-bit phase shifter with an electrical control mechanism. The RF circuit is simply a superconducting microstrip line with three Josephson junctions underneath the ground plane. By controlling the bias current of the Josephson junctions to inject quasi-particles into the ground plane, the London penetration depth changes which subsequently alters the phase velocity.

The 3-bit digital control is provided by three separate Josephson junctions. The first junction covers the microstrip line length for a 180° phase change. The second junction covers half the length of the first one for a 90° phase change. The third junction covers half the length of the second one for a 45° phase change. For an N-bit phase shifter, with N>3, the bisecting car be repeated and more sections added.

An optical version of this 3-bit phase shifter is also proposed (see Fig. 13). A uniform light exposure to each region will provide the required phase shift, by means of quasi-particle injection via pair breaking in the superconductor. The quasi-particle injection can also be accomplished by the use of optical waveguides, using the fringe field of the guided laser light. The expected performance of such a 3-bit shifter is described as follows:

(1) Frequency Range

Since niobium has a cut-off frequency at 700 GHz, the operating frequency for a niobium phase shifter enters the sub-millimeter range. Niobium nitride has a much higher cut-off frequency than that of niobium, and the operating frequency for a niobium nitride phase shifter reaches the terahertz range.

(2) Frequency Band

The phase shift of a TEM mode or quasi-TEM mode transmission line is proportional to the frequency. Therefore, the relative bandwidth of a plain transmission line phase shifter is limited by the tolerance of the phase shift. For instance, according to Equation (19), the step of a 3-bit phase shifter is

$$\Delta\varphi = \frac{2\pi}{2^3} = 45° \qquad (20)$$

If 20% of $\Delta\varphi$, i.e., $\pm 9°$ is the allowed phase tolerance, then the realtive bandwidth can be calculated as follows

$$\frac{\Delta f}{f} = \frac{9° - (-9°)}{180°+90°+45°} = \frac{18°}{315°} = 5.7\% \qquad (21)$$

Even so, the absolute bandwidth for terahertz operating frequencies is very wide (several tens to the hundred of GHz).

(3) Attenuation

The attenuation of a superconducting phase shifter is determined by the total length as well as the attenuation constant of the transmission line. The

attenuation constant of a superconducting line depends on the temperature, frequency and material. For niobium, the attenuation constant is at least an order of magnitude lower than that of the conventional line. For niobium nitride, it is even lower.

(4) Mismatch

For a plain microstrip line, there is no discontinuity causing mismatch, which is the great advantage of a superconducting phase shifter over a conventional one. The phase velocity V_p and characteristic impedance Z_c of a TEM line are given by:

$$V_p = 1/\sqrt{LC} \tag{22}$$

$$Z_c = \sqrt{L/C} \tag{23}$$

When the quasi-particles are injected to vary L, according to Equation (22), the phase velocity changes. At the same time, however, according to Equation (23), the characteristic impedance changes as well. This effect causes mismatch and also changes the attenuation. This mismatch can be minimized by increasing the total length of the line. The longer length requires less change of the inductance L, for the same amount of phase shift. Therefore, it reduces the mismatch. A compromise has to be made in order to achieve a good match and low attenuation at the same time.

(5) Operating Speed

The operating speed of the superconducting digital phase shifter is determined by the switching time of the optical or electrical controlling mechanism. In both cases, the switching time can be shorter than a nanosecond.

The N-bit digital superconducting phase shifter will fulfill a critical need in Terahertz Imaging Radar Systems. Such a phase shifter offers high performance, with very broad bandwidth and low power dissipation. The simplicity of the design makes it possible to achieve a highly integrated circuit by including the phase shifter and other RF devices on a simple chip.

CONCLUSION

In this paper, we have studied the physics of non-equilibrium superconductivity underlying the operation of the superconducting phase shifter. Relations between quasi-particle density, energy gap and penetration depth have been derived. These relations show that quasi-particle injection by external means, can be used to alter the penetration depth and hence, produce stripline modulation. Superconductive transmission lines are seen to be operable to frequencies of hundreds of gigahertz, corresponding to the mm and sub-mm wavelengths required in phased array antennas and other applications. This study shows that the superconducting phase shifter offers high performance, with very broad bandwidth and low power dissipation. This will fulfill a crucial need in the area of mm and sub-mm wave phased array antennas and Terahertz Imaging Radars. A digital superconducting N-bit phase shifter based on the microstrip transmission line is proposed for implementation in Terahertz Imaging Radars.

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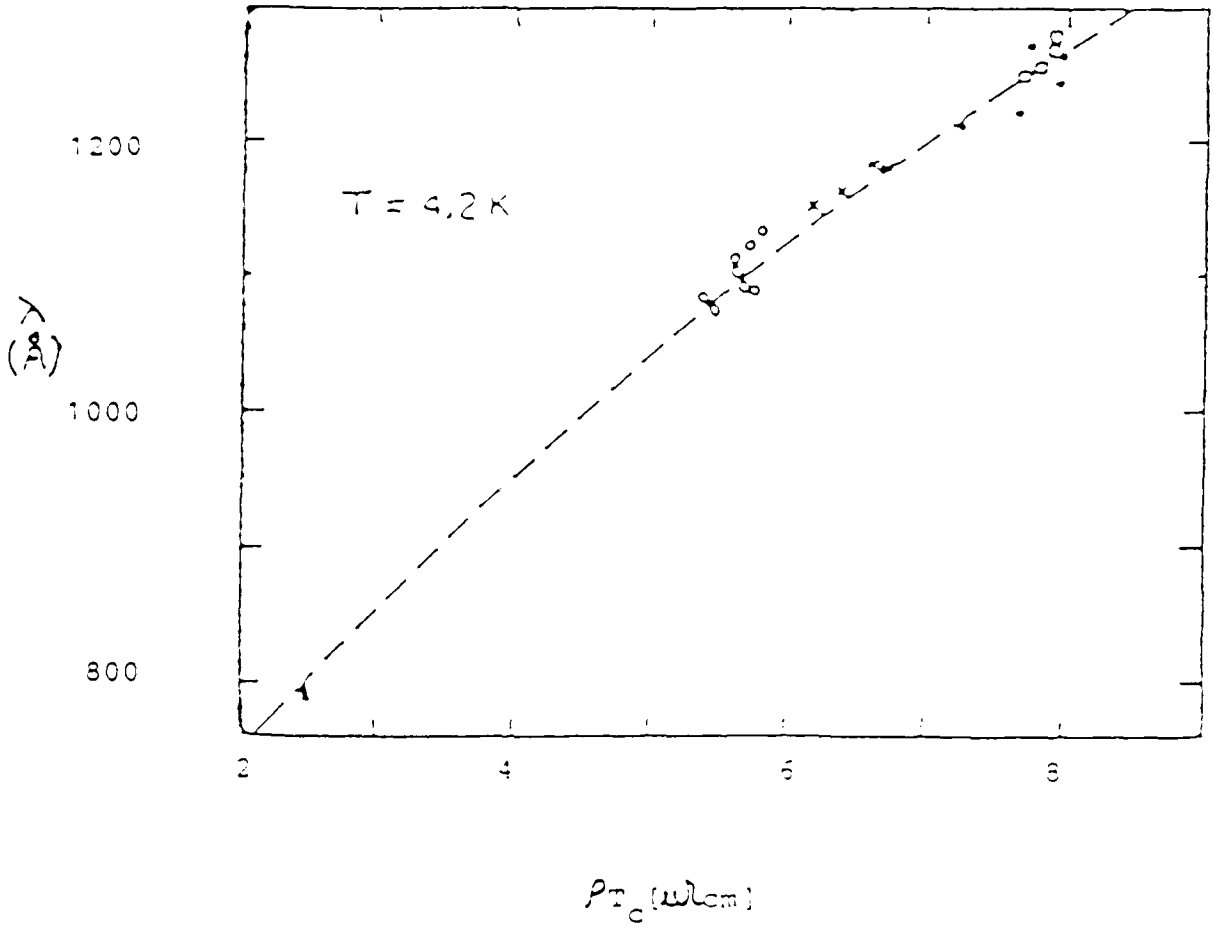


Fig. 1 Magnetic penetration depth λvs. residual resistivity for Nb films, from reference 5.

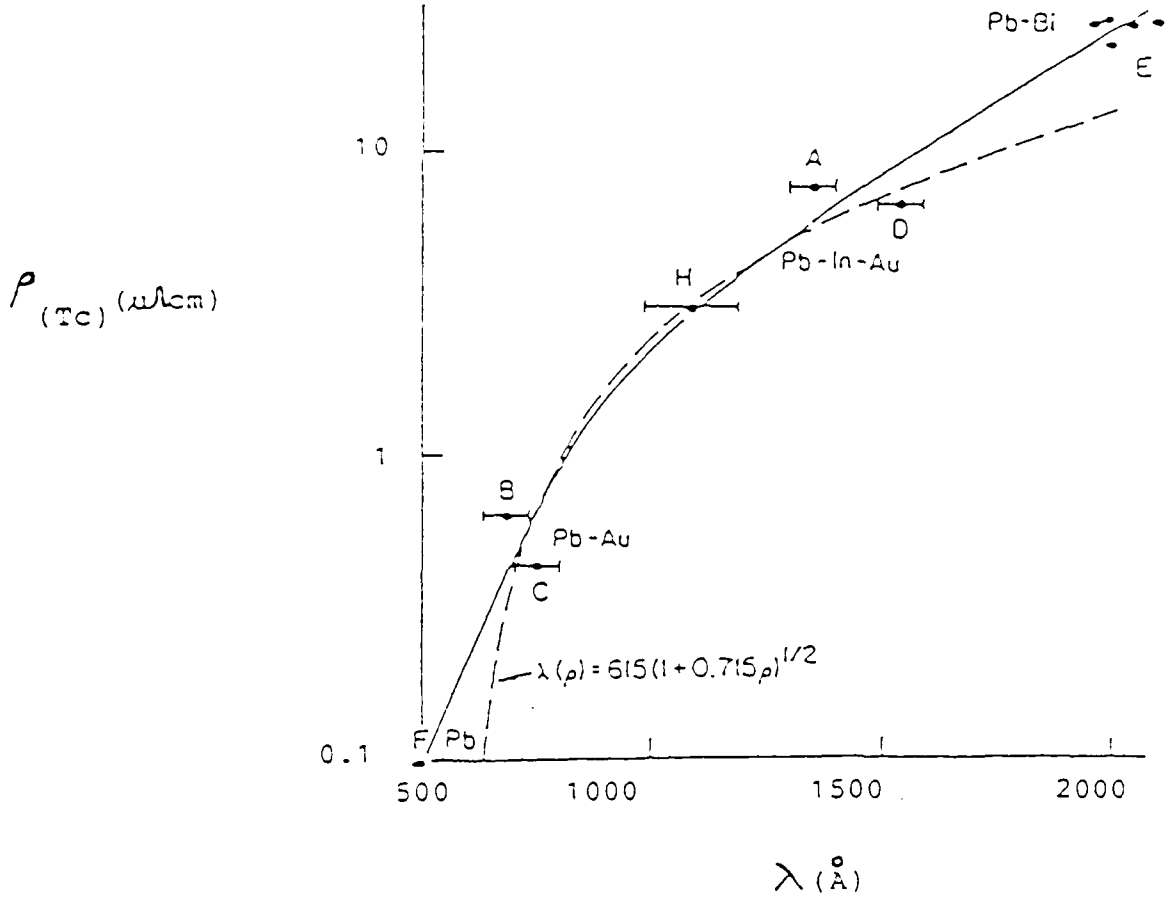


Fig. 2 Dependence of measured penetration depths, at 4.2 K, upon resistivity just above T_c, taken from reference 22, for samples of lead containing impurities.

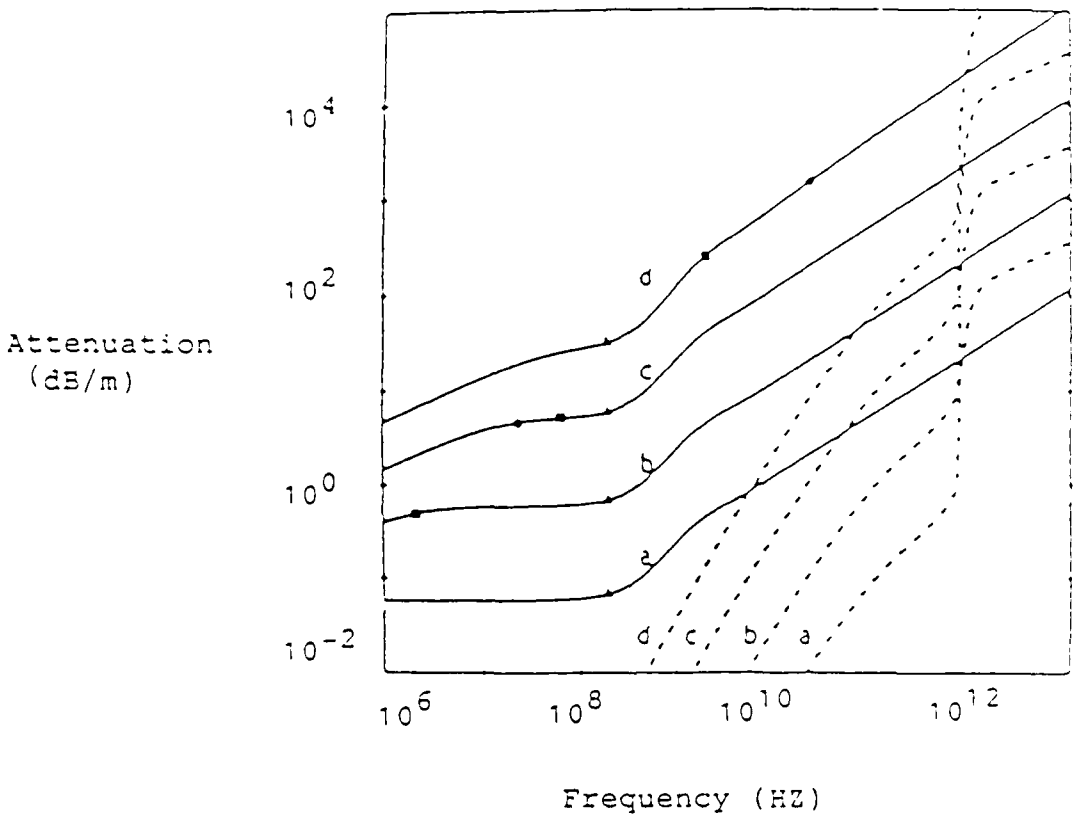


Fig. 3 The attenuation in dB/m of striplines of copper (solid lines) and niobium (dashed lines) at 4.2 K, from reference 12. The results are for a conductor thickness of 1um and a dielectric thickness of a) 200 um, b) 20 um, c) 2 um and d) 0.2 um.

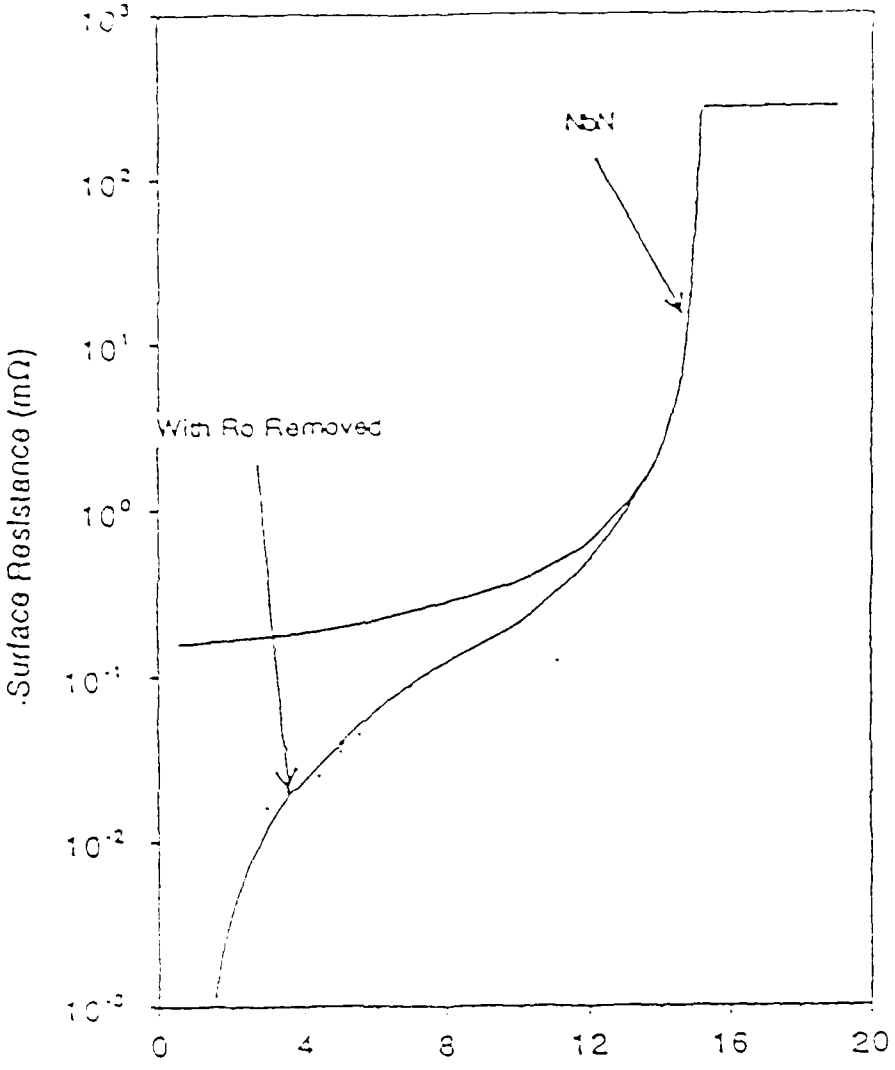


Fig. 4 Some recent results of measurements of surface impedence of NbN fabricated by HYPRES, taken from reference 13.

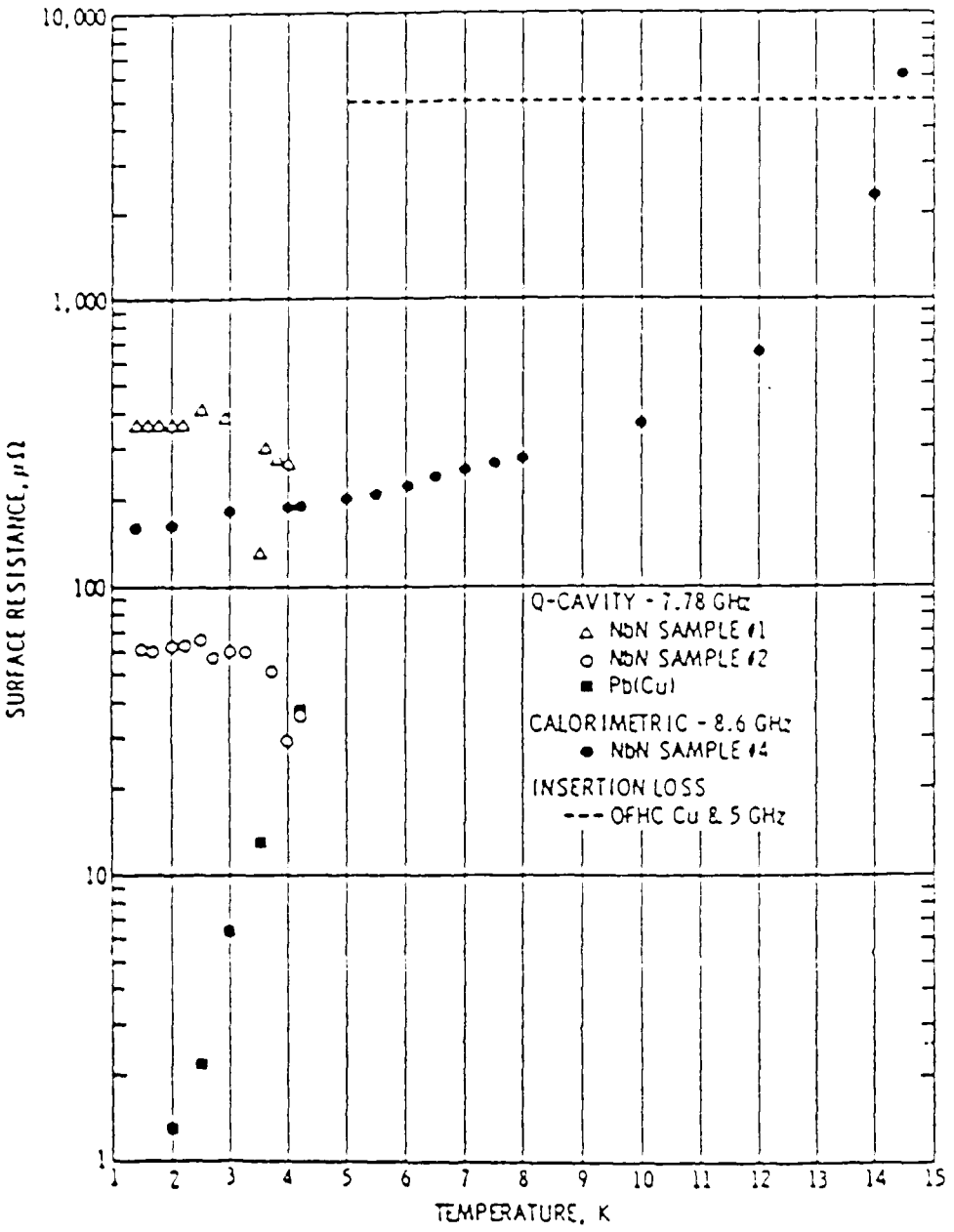


Fig. 5 Surface resistance measurements at 7.78 and 8.6 GHz of NbN samples, fabricated by HYPRES; from reference 14.

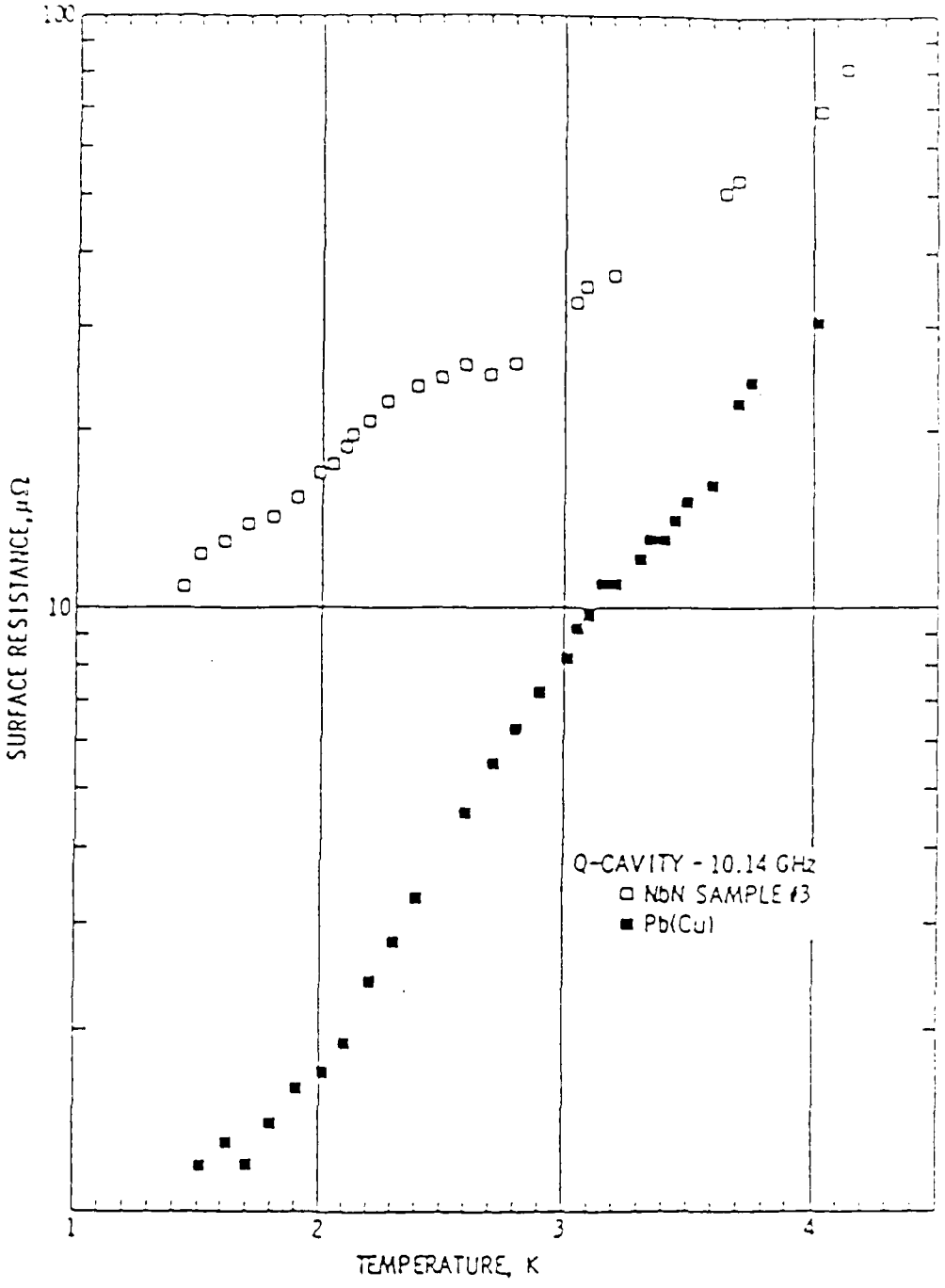


Fig. 6 Surface resistance measurements at 10.14 GHz of NbN samples fabricated by HYPRES; from reference 14.

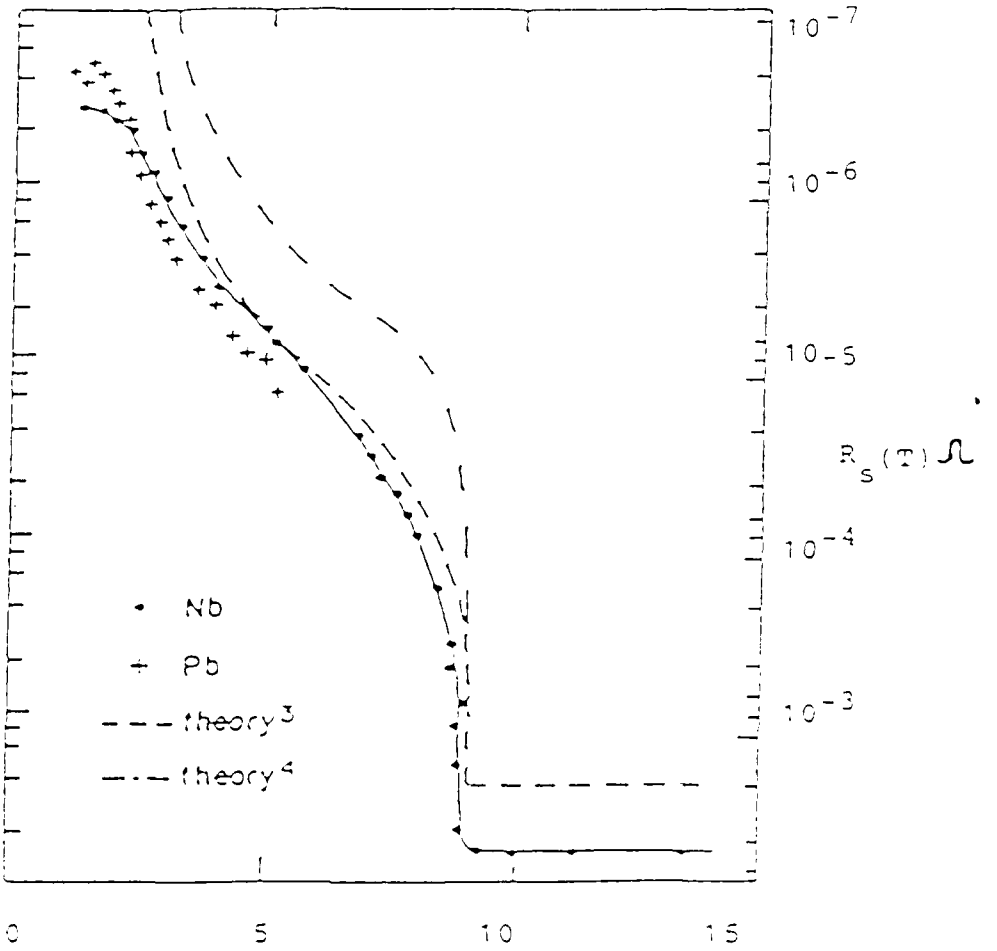


Fig. 7 The variation of the surface resistance of niobium and lead films with temperature, from reference 23.

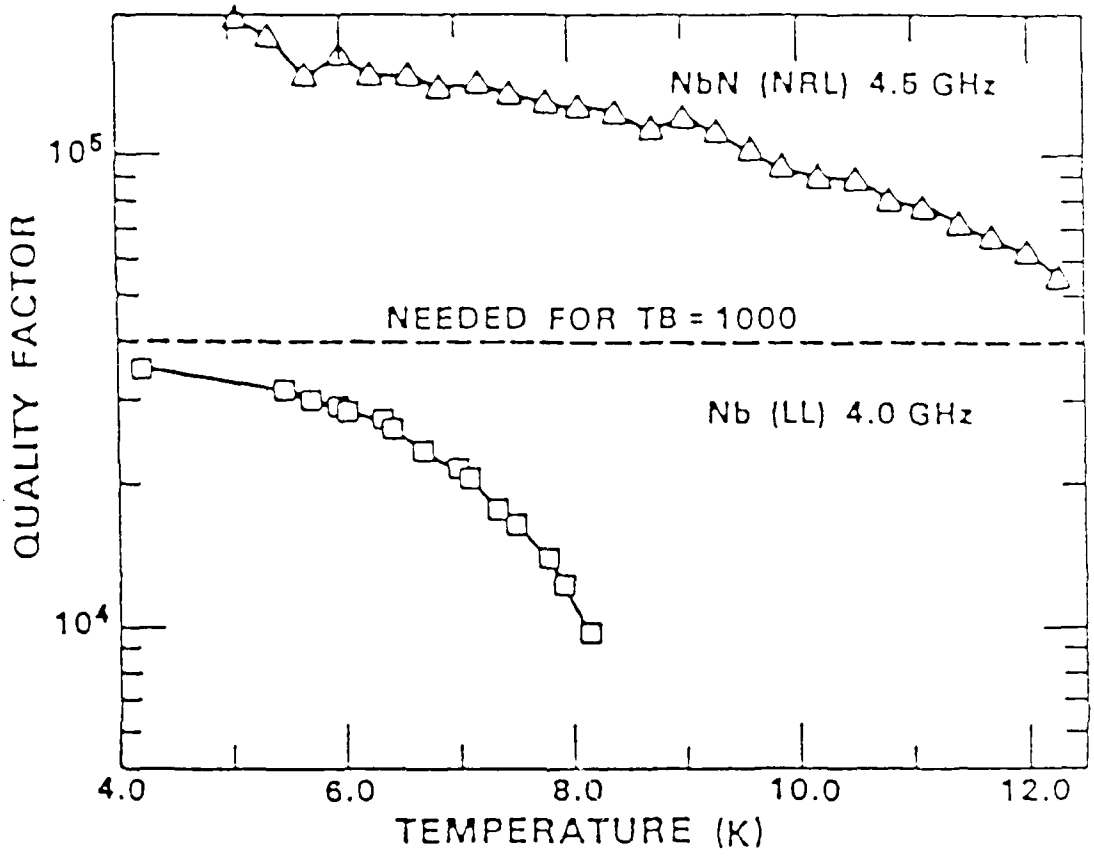
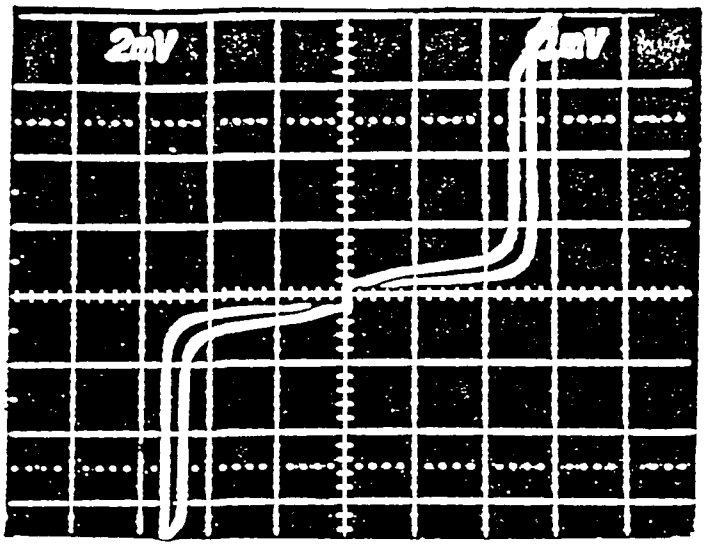


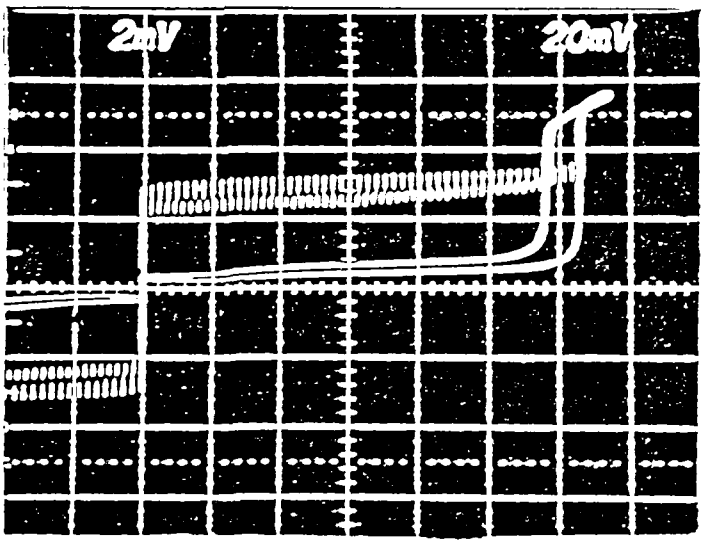
Fig. 8 Results from Naval Research and Lincoln Labs. comparing the RF loss in niobium and niobium nitride as a function of temperature.



I = 0.2mA/div.

V = 1mV/div.

Fig. 9a The I-V characteristics of a Nb-AlOx-Nb Josephson junction, without and with irradiation. Work done at HYPRES.



I = 0.1mA/div.

V = 20mV/div.

Fig. 9b The I-V characteristics of an array of 50 Josephson junctions, without and with irradiation Work done at HYPRES.

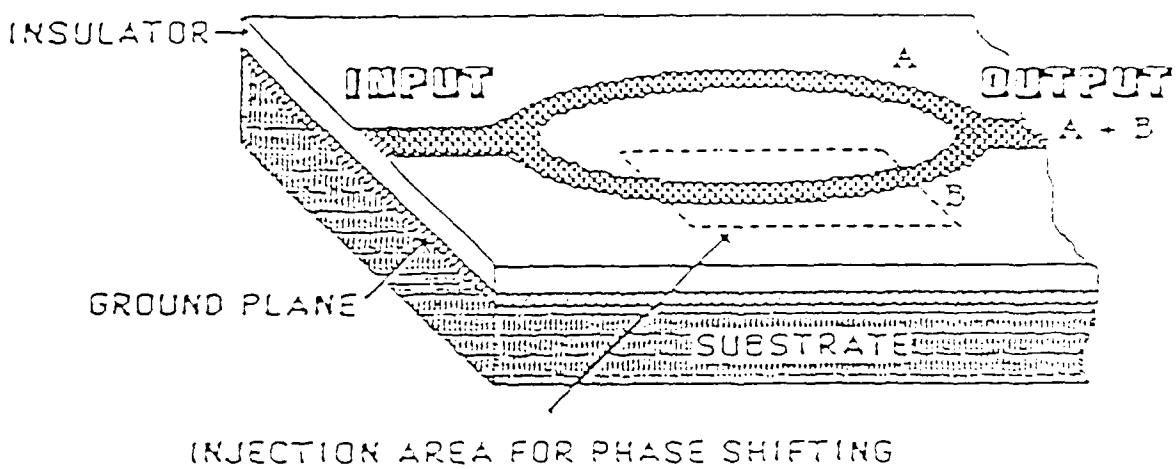


Fig. 10 The superconducting microstrip interferometer.

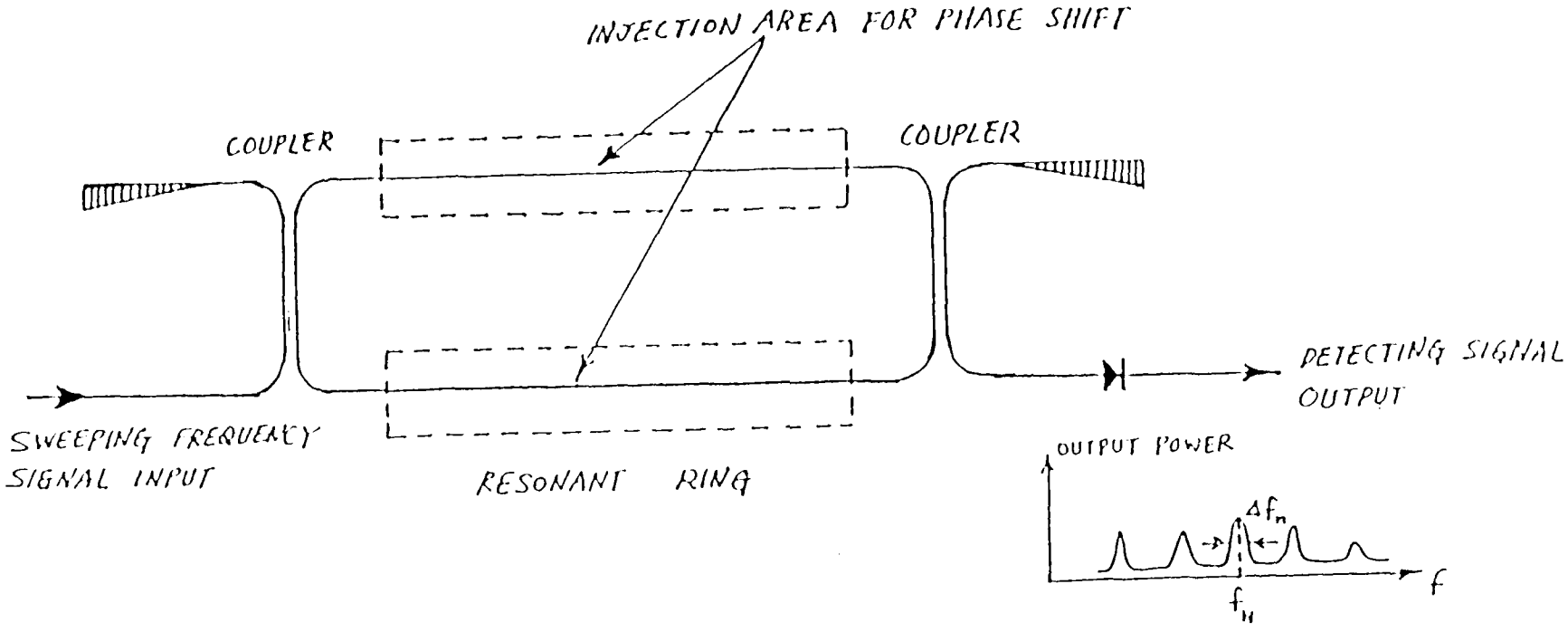


Fig. 11 The superconducting microstrip resonant ring.

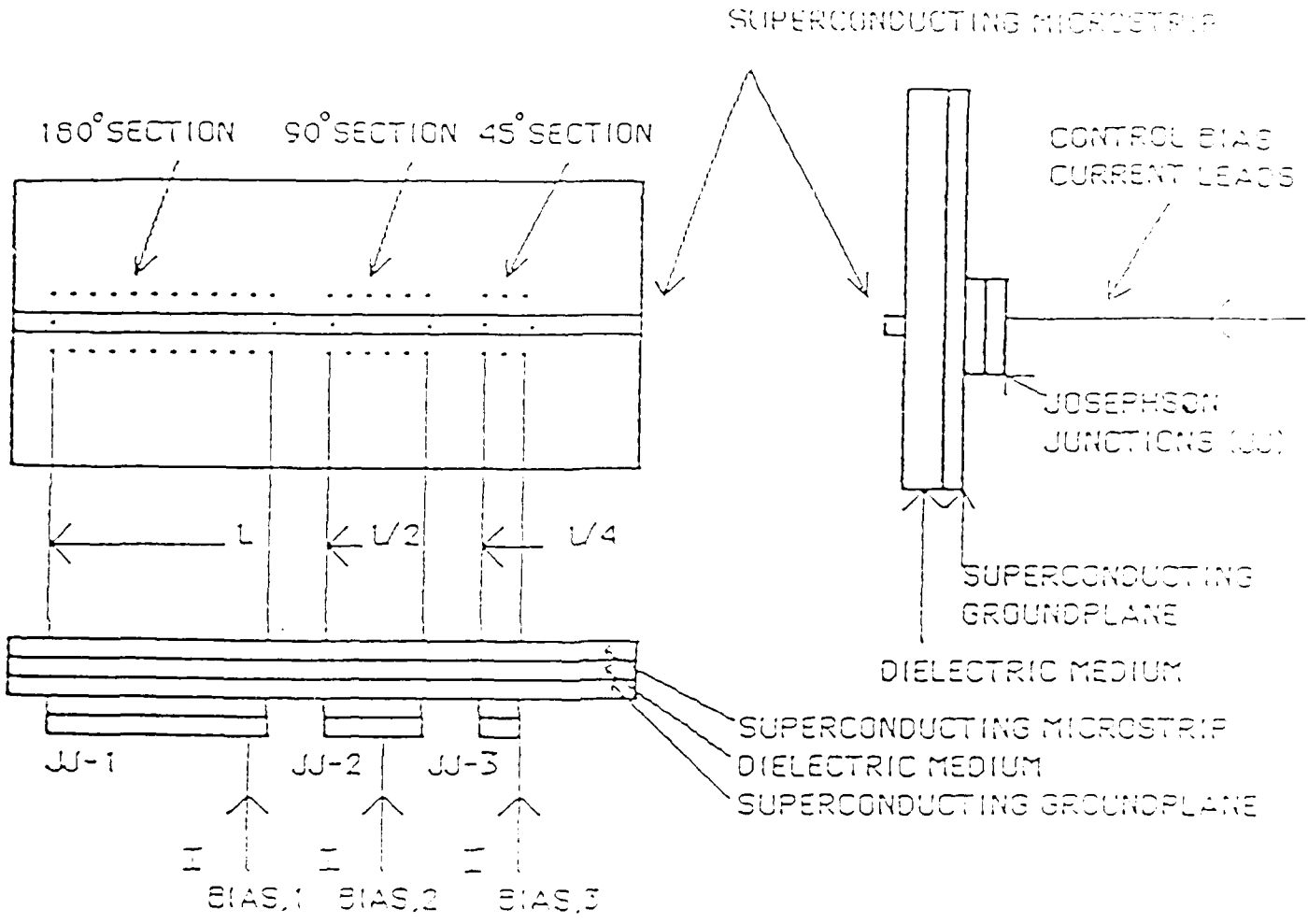


FIG. 12 ELECTRICALLY CONTROLLED 3-BIT PHASE SHIFTER

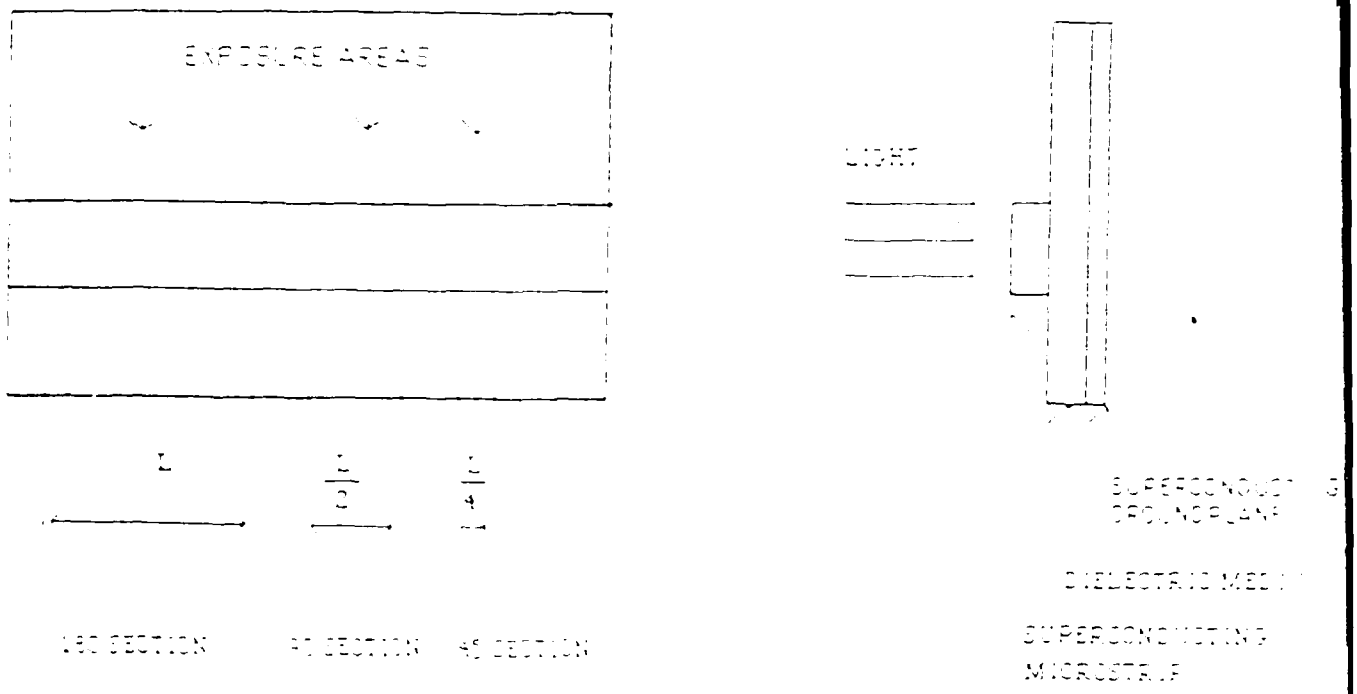


FIG 10 OPTICALLY CONTROLLED 3-BIT PHASE SHIFTER

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